1. **An Investigation to Explore the Critical Zone on Mars (Brantley, PSU)**

Introduction and Targeted Questions

A complex suite of chemical, biological and physical processes combine to create the engine that transforms bedrock into soil within the so-called Critical Zone on Earth. The terrestrial Critical Zone (CZ) is the thin layer defined from the outer limits of vegetative canopy down to the lower limits of groundwater, and it is this zone that supports almost all terrestrial life. Knowledge of the CZ is limited due to the extraordinary complexity of the weathering engine.

We propose to develop a network of terrestrial (and marine) field sites situated along environmental master-variable gradients which will be studied to understand the Critical Zone on Mars and on the early Earth (Figure 1). Physical and biological scientists will work together to measure signatures of life processes recorded during weathering. Parameters to be measured at the CZEN sites will include bedrock, soil, fluid, physical, and biological properties, as well as rates and mechanisms of element cycling. In addition to exploring weathering localities on Earth to investigate the importance of environmental variables in controlling basalt weathering, we will also investigate weathering over geologic time by investigating terrestrial paleosols. Furthermore, studies on terrestrial weathering will be complemented by studies on basalt reactions with seawater (i.e. weathering will include both terrestrial and seafloor weathering) as well as analysis of Martian data.

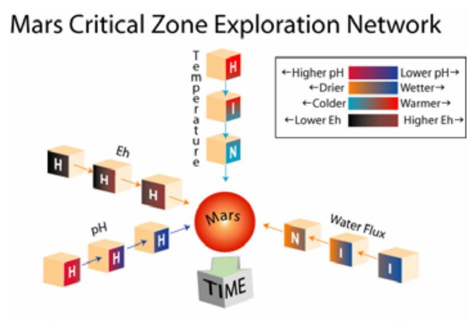

Figure 1. The Mars CZEN: a network of soils developed on basalts that define natural laboratories to investigate the effects of variation in the environmental master variables temperature, precipitation, pH, Eh, and time.

Questions to be addressed. Our team will answer the following three questions:

1) What are the rates and mechanisms of transformation of basalt rock into soil on land or into sediment on the seafloor on Earth, and how far did these transformations progress on early Earth or on Mars?

2) Within the Critical Zone on Earth, what biosignatures are developed and what ecosystems exist at the surface and at depth?

3) Can we find evidence for these biosignatures or ecosystems on Mars or in early paleosols?

3) How have these weathering rates and processes contributed to the possible development and support of life on Mars or development of life on our planet early in its lifetime?

Interdisciplinary Team

The proposal will be spearheaded by a subset of scientists involved in the NAI, including the following people (none of whom have been contacted0: Carnegie (Hans Amundsen, Marilyn Fogel, Andrew Steele, Ed Vicenzi); Indiana (Jim Fredrickson, Tullis Onstott); Marine Biological Laboratory (Katrina Edwards, Jack Mustard, Olivier Rouxel, NASA Ames (David Blake. Allan Treiman, Tori Hoehler, Chris McKay, Norm Sleep); Penn State (Hiroshi Ohmoto, Sue Brantley. Chris House, Clark Johnson, Jim Kasting, Lee Kump, Dave Pollard, Greg Retallack, Ariel Anbar); Berkeley (Jill Banfield, Don DePaolo, William Dietrich, Matt Fantle); Boulder (Tom McCollum); Hawaii (Jeff Taylor)

2. Stable isotopic signature of Mars methane (Pratt, IPTAI)

Methane (CH_4) isotopes have been used to distinguish methane formation mechanisms (biogenic, thermogenic, and abiogenic), quantify mixing processes and identify microbial methane oxidation. These isotopic measurements are being used to study methane cycling on Earth and have been proposed as a way to determine whether methane detected in the Martian atmospheric is biological in origin. To use the stable isotopes to fingerprint Martian methane, measurements of $\delta^{13}C$-CH_4 and $\delta^{2}H$-CH_4 must be made with precisions of <2‰ and <15‰, respectively. Telescopic and remote sensing techniques can quantify temporal and spatial variations in Martian methane concentration; however, the required isotopic precisions can only be realized with ground based techniques. Because no instruments are being developed by NASA for future Martian rovers that possess the requisite analytical precision, we are developing a Cavity-Ringdown Spectrometer capable of rapidly measuring the concentration and C and H isotopic composition of trace amounts of atmospheric methane in the field with precisions comparable to standard laboratory techniques (e.g. Isotope Ratio Mass Spectrometry [IRMS]). We are currently testing both diode and quantum cascade laser sources to target near- and mid-IR absorption peaks and to determine how they influence sensitivity, precision and flight capability. Once the instrument has been successfully field tested at on Earth to quantify microbial production and consumption of methane in permafrost settings, we will optimize the instrument for transport and operation on a Martian lander or rover.

NASA Missions that this research could impact:

The Cavity-Ringdown Spectrometer is one instrument that could potentially fly on AFL and would be a high priority if further telescopic and future satellite observations confirm that spatial and temporal variations in the CH_4 concentration in the Martian atmosphere.

3. Currently Active Mars (Dietrich, Manga, DePaolo. UCB)

Perhaps the greatest surprise about Mars from recent missions is not that it shows evidence of significant water related surface processes in the deep past, but that the current Mars is far from a dead planet. Recorded activity, thanks in part to long-term monitoring and ever increasing resolution of observation, is found to occur at all scales. There are local CO2 eruptions. Avalanching has been noted on dunes. The recently discovered gullies may, in some locations, be currently active. Dust devils sweep across the landscape, and dust storms cross the planet. Ice caps seasonally adjust. The surfaces are still being actively cratered (at least with smaller features). And, although we have not seen ongoing volcanism, there are areas of Mars where volcanism is probably less than 10 million years old, and associated with those eruptions, large canyons were cut by outflowing water. Life diversifies in complex environments, and species diversity typically reaches a maximum at some intermediate level of disturbance.

Questions to be addressed:

1) What water-related processes are *currently* active on Mars, what are the reliable signatures of these processes, and what mechanisms permit the surface and near surface occurrence of water?
2) What environments currently on Mars would permit life to exist (perhaps surviving from earlier more "habitable" conditions)?
a. Might the region between deep, active magma and the planetary surface be a factory for life due to heating generated groundwater circulation and the absence of UV radiation?
b. Could life originating at the surface under earlier more favorable conditions been driven underground with the loss of water and protective atmosphere (if such existed)?
c. Might seepage headed channels, or small gully heads be sites of concentrated life persistence if water is still available at depth?
3) What spatial and temporal gradients of temperature and water would be optimal for the presence and greatest diversity of life?
4) How has life found beneath the ground surface on Earth evolved and arrived at its current location, and influences the patterns of diversity and abundance?
5) What is the history and magnitude of currently active Martian surface processes?

4. Martian Ice: a resource and a scientific record [Schorghofer, UH]

From a resource and exploration perspective, access to water would greatly facilitate missions to Mars and it is therefore important to determine the quantity and geographic distribution of water ice. Scientifically, the ice would reveal the climate history of the planet; it may contain remnant life, if it ever existed, and harbor habitable niches for microorganisms. Table I lists several dual-purpose research areas, and the following text elaborates a few aspects.

Table I: Dual-purpose research topics

	Resource & Exploration	***Astrobiology***
low-latitude ice and frost (about 50°N to 50°S)	where? how much?	melting (e.g. in gullies)? landing sites
mid-latitude ground ice	how much?	landing sites; historical record
residual polar caps / polar layered deposits	how much H2O (versus CO2)?	melting? landing sites; historical record (ice cores)
Capacity of microbial consortia to survive and revive in Mars-like conditions	contamination	indigenous life

The low latitudes are easier to reach with spacecraft and a more comfortable place than the polar regions, for both robots and humans. These generally dry areas represent most of the Martian surface. Ice patches, glaciers, seasonal frost, and gullies have been observed at these latitudes. Existence of H_2O at these latitudes is due to local heterogeneities, as for example topographic slopes. There are initial studies about icerich deposits and ice related phenomena, but existing and incoming data remain to be surveyed and analyzed; models of atmosphere/surface interaction and morphological processes would also be capable of addressing these questions.

In addition to places where ice accumulates today, there are remnants of ice from past but recent climate periods; parts or all of the mid-latitude ground ice are of this nature. Identification, prediction, and characterization of these ice reservoirs requires to understand the recent history of the ice, especially during the last five million years. The residual polar caps and polar layered deposits are likely the oldest ice reservoirs in the near-surface and the prime target for ice coring. For this, we need to predict the stratigraphy of the ice.

Specific projects that could be worked on, relevant to resource exploration and astrobiology, and in preparation for sampling the ice:

•A systematic survey of spacecraft imagery for ice-related and frost-related features to map out their geographic distribution, far more extensive than what has been done so far. This would be a high-visibility project/database.

•Additional studies of specific features that are H_2O related or suspected of being H_2O related (gullies, frost, polygonal patterns, lobate debris aprons, slope streaks, glaciers, and a large variety of polar ice patterns). This work can include data analysis, terrestrial analog studies, and model calculations.

•Develop models for the expansion and retreat of ice sheets, glaciers, and the residual polar caps, and inverse methods for remote-sensing techniques of elemental composition. A number of NAI members have a strong expertise in this subject. Also highly relevant is the study of terrestrial analogs in the Dry Valleys of Antarctica.

<u>NAI collaborators:</u>
Hawaii: Norbert Schorghofer, Jeff Taylor
Colorado: M. Mellon, B. Jakosky
NASA Ames: C. McKay, J. Heldman

5. Mars As An Active Planet (Mumma, GSFC)

Team Players: Goddard, UCLA, PSARC, Carnegie, Arizona, plus others (? TBD).

6. Volatile sulfides as atmospheric biosignatures (Pratt, IPTAI)

Biological production of volatile and soluble sulfide compounds in Earth's oceans and salt marshes produces a substantial sea-to-land transfer of sulfur and a distinctive biosignature in the atmosphere. In addition, biogeochemical cycling of volatile sulfide compounds is inferred to be an important pre-anthropogenic component of Earth's climate system through oxidation and generation of cloud-condensing nuclei. Given extensive deposits of mineral sulfate on the surface of Mars and detection of trace-level methane in the atmosphere, it is critical to test and refine spectroscopic, chromatographic, and stable isotopic methods for determining the composition and concentration of volatile and soluble sulfide compounds at natural abundances in water and gas samples. Experimental studies are needed to assess reaction mechanisms for abiotic production of simple compounds like methanethiol and dimethysulfide, as well as more complexly branched sulfide compounds, in the crust and deep interior of Earth and Mars.

NASA Missions that this research could impact:

If volatile sulfide compounds of biological origin can be distinguished from those of abiotic origin, then it would be extremely important to search the atmosphere for these compounds and characterize their isotopic composition. This could either be done by the Astrobiology Field Laboratory (AFL) with either a gas mass spectrometer or long path length laser spectrometer or any future orbiter carrying high resolution IR spectroscopy (future Scout or strategic missions). In the latter case, these observations could be vital to landing site selection for the AFL and rover/lander missions beyond AFL.

7. Remote detection of gas hydrate on Earth and Mars (Pratt, IPTAI)

Independent detections of methane in the Martian atmosphere suggest the presence of substantial quantities of solid gas hydrate in the subsurface. At a surface temperature of 200 K, the stability field of methane hydrate extends from a minimum depth of ~15 m (corresponding to a confining pressure of ~140 kPa) to a maximum depth of as much as a kilometer below the base of the cryosphere. Within this region, methane hydrate and, potentially, carbon dioxide hydrate may be present in concentrations ranging from a dispersed contaminant to massive deposits. Methane hydrate is ubiquitous in permafrost regions on Earth but its abundance on Mars is unknown. As potential indicators of past or present biological activity, identifying the distribution and composition of hydrate in the subsurface through the use of geophysical methods can help target more focused investigations. We propose collaborative laboratory experiments utilizing direct spectroscopic methods combined with dielectric and electrical conduction properties of hydrate-mineral mixtures (including both methane and carbon dioxide hydrate) over the frequency range used by current and planned radar sounding investigations of the Martian subsurface. These methods will be used in conjunction with ground penetrating radar (and other electromagnetic) to interrogate hydrate-rich permafrost environments on Earth in order to evaluate viability of remote detection of subsurface hydrate on Mars.

NASA Missions that this research could impact:

ESA Express's MARSIS and MRO's SHARAD experiments will rely upon informed interpretation and well-constrained modeling of satellite ground penetrating radar. The proposed experiments would provide critical input into this process now. The determination of whether CH_4 hydrate exists in the Martian crust would further constrain the origin of atmospheric CH_4 and could determine the likelihood that it is derived from an active biological site. As a result the outcome of the proposed research will impact landing site selection for AFL. The determination of whether CH_4 or CO_2 hydrate exists in the Martian crust will impact models of Mars climate and geology, which could impact landing site selection for MSL as well as AFL.

8. Review current and planned missions to increase impact on Astrobiology, prepare participating scientist proposals (PSP) (Mancinelli, SETI)

- Cassini: PSP for Astrobiology data on Titan and Enceladus
- MSL: PSP for data analysis plan

- AFL: Refine the list of astrobiological measurements to be made during the mission as well as the accompanying instrumentation.
- MESSENGER, Dawn, New Horizons, etc.: review prospects for data possibly relevant to Astrobiology

Moon: Radiation damage experiments. Effects of UV and ionizing radiation on cell survival/health.

10. Lunar Stratigraphy and the possibility of finding pieces of Early Earth. (Woolf. UA)

The only easily available observation of the lunar strata layer and its depth before a possible "bedrock" is in the walls of lunar craters. For crater diameters of a few km, the depth is enough to see whether there is a deep suite of strata or not, and without the walls being glazed by the impact.

A small camera with telephoto lens landed in a crater can view everything from a complete stretch of wall, down to seeing detail a few mm. across if that is not covered by dust or by the welding effect of hot impact debris.

The "Earth attic paper" suggests a depth of regolith that could be ~1 km. This could be hopelessly overestimated, and pictures would likely reveal the true story, where there are igneous layers etc.

11. Examination of dust cover versus time of day for the walls of lunar craters (Woolf, UA)

Nobody knows what to expect of dust cover versus time of day for the walls of lunar craters. There is an opportunity for an imaging small lander mission that might do anything from identifying the lava flow layers to identifying cm sized pieces of non-lunar material.

12. Examination of Lunar Dust (Woolf, UA)

In assessing the future usefulness of the moon for astrophysical and astrobiological telescopes, the big unknown is dust. A small lunar lander that contained a DISCOVR type camera would be useful both for exploring this, and give Earth Science and TPF a taste of examining a planet at low angular resolution.

13. A combined Astrobiology Earth Sciences mission (Woolf, UA)

A combined Astrobiology Earth Sciences mission for the Moon that might or might not be combined with a demonstration of the difficulties or otherwise of observing in the presence of levitated lunar dust. If without the dust, it could be done from a lunar orbiter, or an Earth-Moon L1 device.

It is possible to use the observations to test the dust problem if they are made with a small lander of the payload that Pete Worden wants to make. It is possible to produce pictures showing the Earth weather patterns as Earth rotates, and slowly changes phase because of the motion of the moon. I think these might make fun 15 second bites with the evening news weather reports. Simultaneously there could be a mid IR observation. so that both day and night weather would be seen.

The science includes:

a) Earth Science: Tying together observations from GEO satellites because they don't observe the same piece of Earth at the same time.

b) Astrobiology: Looking at the glint of the sun reflected from water and assessing the usefulness of this as part of the observations for a TPF.

14. Examination of Psychrotolerant Microorganisms in Simulated Martian Environments (Onstott, IPTAI)

Upcoming Mars lander and rover missions will be collecting Martian surface and near subsurface samples and performing wet chemical, electrochemical and organic analyses on them. Knowing the fate of rover borne terrestrial microorganisms and of organic compounds in simulated Martian environments, therefore, will be essential for meaningful interpretation of these analyses and for the design of cleaning protocols that will prevent forward contamination of the Martian environment. To date experimental efforts have mainly tested the survivability of bacterial spores on spacecraft materials under simulated Martian conditions and have established the importance of Martian UV flux in debilitating spores. The same experiments demonstrate how dust readily shields microorganisms from the harsh UV flux. We propose initiating a rigorous experimental program based upon challenging psychrotolerant aerobic and anaerobic microorganisms with simulated Martian environments protected from direct UV exposure by regolith materials but still exposed to diurnal variations in temperature and humidity and in the presence of a Martian atmospheric composition at Martian atmospheric pressure. These experiments are design to test the *in situ* metabolic and catabolic rates, the stress response, and the survivability of these microbes, and the relative stability of cellular organic matter. We're also proposing to analyze the samples resulting from these experiments with the same instruments that are being flow on Mars lander and rover missions. In this regard we have established collaboration with Prof. Kounaves at Tufts University to examine the potential electrochemical signatures that may arise in Martian surface samples, in particular contrasting the UV photoactive layer with the visible photic to subphotic zone immediately beneath it by vertically profiling inoculated regolith microcosms. The electrochemical profiles will be compared to profiles of the geochemical, TEM, organic analyses and microbial respiration activity measurements of the microcosms. We have performed initial experiments in collaboration with Prof. Schuerger at Kennedy Space Center, but the time available for these experiments at the Kennedy facility are extremely limited. Another Mars simulation chamber with better capabilities than the one at Kennedy for performing these experiments has been made available to us at SHOT, Inc. in Indiana, but additional funding is required if this facility is to be kept open.

NASA Missions that this research could impact:

The results of these experiments will not only significantly advance models of forward contamination by robotic craft of Martian habitats, but will also provide a firmer foundation for distinguishing biotic from abiotic signatures of Martian soils and for ascertaining the habitability of the Martian environment. These experiments will directly benefit the Phoenix lander and the MSL missions and will impact development of planetary protection protocols and instrument selection for the AFL.

16. Molecular Microbiology of the Terrestrial Subsurface (Macalady, PSU)

Several bodies in this solar system are judged to have the potential for life, but inhospitable surface environments (e.g., Mars, Europa). The terrestrial subsurface remains largely unexplored, but has the potential to provide our only model for detection limits, biogeochemical signatures, spatial variability, and evolutionary rates of microbial subsurface life. Improved understanding of terrestrial subsurface life, including it's spatial and temporal relationships to tectonic events and extraterrestrial impact fracturing, will contribute essential information to missions to planets such as Mars, planetary bodies in the outer solar system, and future efforts to search for life beyond our solar system.

NAI investigators with expertise and/or potential interest (partial list):

Jenn Macalady (PSARC)--proposer
Chris House (PSARC)
Tullis Onstott (IPTAI)
Barbara Sherwood-Lollar (IPTAI)
many other IPTAI members
Jill Banfield (UC Berkeley)
Mitch Sogin (MBL)
Norm Pace (CU Boulder)
John Spear (CU Boulder)

International investigators with NAI ties:

> Charles Cockell (Open University, Centre for Earth, Planetary, Space and Astronomical Research)

17. Interactions within microbial communities during colonization of analogs of currently active Mars habitats and potential biosignatures (Roden, Emerson, UCB)

In the context of a still active Mars, renewed focus on microbial communities that may populate the likely habitats seems appropriate. Despite the lack of perfect analogs on Earth, terrestrial environments with a subset of the relevant characteristics can be identified. Enormous progress has been made in defining the membership and organization of microbial consortia in such systems. However, much remains to be learned about microbial function, in situ. In particular, the inter-organism interactions that enable consortia to establish and survive remain poorly understood. This question is timely because only now are the tools on hand that are needed to simultaneously monitor activity in coexisting organisms in ecosystem context and to interpret their biosignature record.

Questions to be addressed:

1) How are biochemical functions distributed amongst members of natural consortia and can these be detected and understood by analysis of succession? (i.e., how does partitioning of function amongst community members change as communities establish, starting from the first colonization event).

2) As communities establish, what sorts of structures (community architectures) emerge? In addition to affecting each other, communities structure their environments: how does the process of colonization modify the surrounding physical and chemical environment? Specifically, what types of biosignatures develop as colonization proceeds (isotopes, organic molecules, trace elements, minerals) and how do subsequent processes (including time) modify these biosignatures?

18. Signs of subsurface life - past and present (Macalady, PSU/MBL)

Absence of liquid water, oxidizing conditions and radiation flux are not compatible with the occurrence of living organisms on or near the surface of extraterrestrial, solar system bodies. In contrast, life or biosignatures of ancient life may exist in subsurface environments where transient or persistent liquid water, reduced radiation flux, and conditions more favorable to life might occur. Important research objectives that can inform the design of NASA missions include

1. Map the range of terrestrial subsurface environments where life occurs;

2. Map the range of subsurface energy sources that can support life;

3. Determine the lowest population densities, congruent with minimal energy sources, required for persistence of life;

4. Identify the range of population structures for subsurface life including both abundant and rare organisms;

5. Develop sensors to detect the lowest levels of biologically induced chemical disequilibria;

6. Employ genomic techniques to understand how subsurface organisms cope with nutrient depletion, electron acceptor limitation, pressure, temperature and radiation stress;

These topics compliment the Berkeley questions: *A. Currently Active Mars (Dietrich, Manga, DePaolo)* and *B. Interactions within microbial communities during colonization of analogs of currently active Mars habitats and potential biosignatures (Roden, Emerson)* and Penn State's *Molecular Microbiology of the Terrestrial Subsurface*

19. The Rare Biosphere Initiative (Sogin, MBL)

Microbial diversity is much greater than previous estimates based upon conventional molecular techniques. Dominant populations have masked the detection of low-abundance organisms, their overwhelming diversity, and their individual distribution patterns. The rare biosphere might serve as a potentially inexhaustible reservoir of genomic innovation, which might explain how microbial communities recover from environmental catastrophes and why every new microbial genome sequence offers so much genetic novelty even when compared to closely related taxa. Members of the rare biosphere might be the products of historical ecological change but have the potential to become dominant in response to shifts in environmental conditions, e.g. when local or global change favors their growth. This initiative would explore how the "rare biosphere" contributes to biogeochemical processes and emergent properties of ecosystems, how it influences shifts and evolution of community structure, and a delineation of its contribution to reshaping genome architecture in diverse microbial taxa. We are also intrigued by the idea that rare taxa might be natural laboratories for genomic and phenotypic innovation including transition stages between the distinct, different metabolic types that we see in the known microbial world – the microbial equivalents of "missing links". This initiative must include the development of a theoretical and analytical framework to model dynamics of microbial communities with the overarching goal of developing a paradigm for predicting how shifts in microbial population structures influence habitability.

20. Organic Cycling of Nitrogen, Phosphorus, and Iron (Fogel, CIW)

N, P, and Fe are all in limited supply for optimal growth of life on Earth. Even with ample supplies of carbon or available water, without these other nutrients organic substances would not have biological importance. Understanding how they might be cycled on Mars, Europa, and super Earths is an intriguing challenge. For example, N_2 is at low abundance in the Martian atmosphere, and it is unknown what N pools are present in Martian rocks. Phosphorus is a major a constituent in common minerals, yet these minerals are inert to Earth's organisms. Iron, while abundant on Mars, is not in the oxidation state needed for terrestrial organisms. Studies could include designing hydrothermal reactions with N and P added, in addition to carbon substrates. Studying how N and P are complexed into organic matter in rocks, meteoritic, and cometary material, measuring isotopic compositions, and comparing those phases to biochemicals would help to distinguish whether biological reactions could have been involved in N, P, and Fe cycling.

21. Earth As An Exoplanet (Mumma, GSFC)

The search for life beyond the Earth is at the core of the NASA mission, and a principal scientific objective of the Vision for Space Exploration is to "conduct advanced telescope searches for Earth-like planets and habitable environments around other stars". NASA plans to launch a series of planet finding and characterization missions over the next few decades, and the development of astronomical techniques to detect signatures of life, or biomarkers, on extrasolar planets is central to the Vision. One biomarker that has been extensively studied on the Earth – still the only planet known to harbor life – is the "red edge" signature of terrestrial vegetation.

The strong increase in the reflectivity of plants beyond around 700nm wavelength has been quantified using a variety of "vegetation indices" within the Earth remote sensing community, e.g. the Normalized Difference Vegetation Index (NDVI). As an interesting historical aside, the first spectral measurements of vegetation were performed by Vesto Slipher to support Percival Lowell's quest to detect vegetation on Mars! (Lowell and Mars, W. G. Hoyt, 1976).

Terrestrial planet detection is a very challenging problem in observational astronomy. For the foreseeable future, space telescopes will only detect the disk-averaged light from extrasolar planets, and even then with low spectral resolution and relatively low signal to noise ratios. Techniques to extract information from such disk-averaged spectra will need to be developed to confidently detect biomarkers and to reject "false positive" spectral features.

Fortunately the disk-averaged light of the living Earth can be used as a test case for the terrestrial planet finding missions. "One shot" measures of the Earth have been obtained by planetary space missions (e.g. Galileo and very recently MESSENGER), but the EPOCh mission will obtain ~5 separate 24-hour observing sessions of the Earth from distances between ~10 – 16 million miles (0.11 – 0.17 AU) using the reused Deep Impact spacecraft and instruments. EPOCh was recently selected for further study as a Discovery Mission of Opportunity, and D. Deming of the Goddard NAI Team is the PI. EPOCh will obtain images of the Earth's vegetation red edge using filters in the red and near IR. The spatial resolution will vary between 26 – 44 resolution elements, which is intermediate between the detailed global Earth remote sensing data and disk-averaged observations.

EPOCh's observations will provide invaluable data to validate the Earth model developed by the Virtual Planetary Laboratory (VPL) under NAI funding. However, this Earth model can be enhanced by incorporating into it more of the data obtained by the Earth Observing System (EOS) missions. For example, the MODIS instrument routinely generates cloud-free global vegetation index (or red edge) maps every 16 days, and maps of the surface reflectance in 7 bands in the vis/near IR every 8 days. We propose to incorporate MODIS products into the VPL Earth model to support the EPOCh mission. This improved VPL Earth model will also benefit analyses of Earthshine, the light reflected off the dark side of the moon, will also aid the interpretation of observations of the Earth that may eventually be obtained from small lunar telescopes as proposed by M. Turnbull (Carnegie & STScI).

Collaborators: Pedelty (Goddard), Meadows (Caltech/VPL), Turnbull (Carnegie), Woolf (Arizona), Deming (Goddard), plus others (? TBD).

22. Earth's First One Billion Years (Ohmoto , PSU)

Synopsis

To understand the origin, evolution and distribution of life on Earth and other planets, and to develop effective methods for search for past and present life on other planets, it is essential that we increase our understanding of the Earth's first one billion years of history, specifically the **connections** among the evolutions of: (1) the Earth's interior structure, thermal structure, and tectonics; (2) the oceanic and continental crusts; (3) the atmosphere and oceans; (4) the climate; and (5) marine and terrestrial biospheres. Examples of specific questions include: (a) When did the magnetic field develop? (b) When did the plate tectonic begin? (c) Were the oceans hot or cold? (d) Who lived on land and in the oceans? These questions can only be answered from comprehensive multidisciplinary researches (geophysics, tectonics, geology, petrology, mineralogy, (bio)geochemistry, etc) on all types of rocks that formed prior to ~3.5 Ga in different parts of the world (e.g., Greenland, South Africa, Australia, Canada, Russia, and China). I propose to formulate a NAI collaborative research project to study the earth's first one billion years.

Potential Investigators from the NAI Teams

Ames: David DesMarais, Chris MaKay
Arizona: Alex Pavlov
Carnegie: Marylin Fogel, George Cody
Colorado: Steve Mojzsis
Indiana: Ed Ripley
UC Berkley: Don DePaolo
UCLA: Ed Young, Jim Lyons, Craig Manning, Bill Schopf, Bruce Runnegar, Mark Harrison
Penn State: Jim Kasting, Lee Kump, Mike Arthur, Kate Freeman, Sue Brantley, Brian Stewart, Rosemary Capo, Martin Schoonen, Clark Johnson, Greg Retallack, Paul Knauth

23. CO Cycling in Anaerobic Environments and Implications for Ancient Metabolisms. (Ferry, House, PSU)

Although CO is an important trace gas, very little is known concerning CO cycling in anaerobic environments or the microbes involved. A collaborative effort is proposed to measure CO flux in diverse anaerobic habitats, conduct a metagenomic analysis of selected environments, and isolate and characterize CO-utilizing species. The results are expected to clarify the role of CO, anaerobes, and anaerobic environments in the global carbon cycle. A recent investigation of the methanogenic archaeon *Methanosarcina acetivorans* revealed an unusual pathway for CO metabolism of potentially ancient origin (2) that impacted the early evolution of life on Earth (1). This result is consistent with recent suggestions that the atmosphere of early Earth contained substantial amounts of CO that contributed to organic synthesis (3). Thus, the isolation and genomic/physiological characterization of anaerobic CO-utilizing species is expected to reveal novel metabolic processes that will aid in the reconstruction of early evolutionary events.

1. Ferry, J. G., and C. H. House. 2006. The stepwise evolution of early life driven by energy conservation. Mol Biol Evol 23:1286-1292.
2. Lessner, D. J., L. Li, Q. Li, T. Rejtar, V. P. Andreev, M. Reichlen, K. Hill, J. J. Moran, B. L. Karger, and J. G. Ferry. 2006. An unconventional pathway for reduction of CO2 to methane in CO-grown *Methanosarcina acetivorans* revealed by proteomics. Proc. Natl. Acad. Sci. U.S.A. e-pub ahead of print.
3. Miyakawa, S., H. Yamanashi, K. Kobayashi, H. J. Cleaves, and S. L. Miller. 2002. Prebiotic synthesis from CO atmospheres: implications for the origins of life. Proc Natl Acad Sci U S A 99:14628-31.

25. Concept design and development for instruments on landers and rovers to survey organic material on planetary surfaces (Allamandola, ARC)

The ultimate aim is to develop a rover/lander-qualified instrument that is capable of remotely surveying the distribution of organic and mineral matter on or slightly below the surface of normal and icy terrain. An instrument of this type could detect the presence of a variety of species including PAHs, potential biomarkers, organometallics, minerals, and impurities in water and water ice, serving both science and as a resource quality determiner. The concept is based on time-resolved, laser-induced fluorescence. This is a novel technique for planetary exploration. It has the advantage that it is capable of characterizing organic material from substantial stand-off distances. This instrument is quite versatile and could become an important part of upcoming NASA missions. It squarely addresses Strategic Goal 3, Sub-goal 3C and Strategic Goal 6 of NASA's 2006 Strategic Plan. Due to the extreme sensitivity of laser-induced-fluorescence, the LIFT instrument can detect complex organic molecules including polycyclic aromatic hydrocarbons (PAHs), nitrogen containing aromatics such as chlorophyll, unsaturated hydrocarbons such as alkenes and alkynes, amino acids and so on, at distances ranging from less than a meter to many tens of meters under favorable conditions. These include the major classes of organic molecules in meteorites. In principle, when deployed, the instrument can be used to overlay the distribution of organics it reveals on conventional photographs and thermal imaging maps etc. of the same area. This will add more geological information about the surface and guide follow-up work whether it is sample return or deeper surface analysis.

Looking to the future, there is no reason this concept cannot be adapted to human exploration. This class of instrument could enable astronauts to quickly and precisely survey a site for follow-up resource evaluation. For example, if ice is found on the moon, this could be used to help determine its purity. This instrument provides a first cut, nondestructive method of assessing materials by simply pointing and 'looking'. The instrument has few moving parts and doesn't require a surface sampler and manipulator, making it a low-cost and low-risk investment with potentially high payoff.

26. Astrobiological Instrumentation Development for Life-detection Missions (A. Steele, CIW)

The currently scoped Astrobiology Field Laboratory was designed to be capable of life detection on Mars. Among the most serious limitations faced by this mission, and every other "life detection" mission, however, is instrument availability and sample preparation technology. These capabilities are extremely important to robotic space flight and have many spin-off uses as well within the space program and the commercial sector. Instrument development and testing for astrobiology have been mainstays of the ASTEP and ASTID programs, but the integration of these programs with NAI activities has been minimal to date. The NAI contribution to new instrument development should be reassessed and potentially augmented to allow cost-effective and accurate measurements that will fulfill astrobiological mission goals.

27. Validation of advanced *in situ* measurement techniques for complex organics. (Mumma, GSFC)

Detecting any sign of life, extant or extinct, on Mars or other solar system bodies will require a new generation of instrumentation and *in situ* measurement approaches. Researchers around the world are studying relevant fundamental processes and biosignatures that may or may not be useful in potential missions such as the Astrobiology Field Laboratory (AFL) on Mars and subsequent robotic and human exploration of the solar system. The NASA Astrobiology Institute (NAI) is unique since it encompasses astrobiologists who study what makes life (as we know it and as we do not) and researchers who have experience with NASA's mission-based exploration strategy as well as working relationships with engineers. We propose to form a group within NAI composed of scientists from different institutions and backgrounds to partner with engineers and instrument designers. The charter of this group would be to first decide what is astrobiologically most significant to detect on Mars, then to determine what technological developments need to be accomplished in the next ten years to advance them enough to be worthy of consideration for flight. The guiding thesis is that multiple, cross-correlating measurements by several techniques must be made to assure the highest fidelity results, given the unknown environment and engineering limits. This approach is far broader than the usual instrument development approach within NASA since it marries researchers, who are asking the right questions on Earth and who may not have considered how their approach may be adapted for NASA missions, with researchers who are well versed in what is necessary for a mission to succeed, but who may not be aware of emerging, multi-sensor techniques which need the time to mature.

One nascent example of such a confluence of expertise has been the merging of a group of established analytical techniques to trace a broad pool of "potentially biogenic" organic molecules in a complex sample and to search for any enantiomeric excess therein. Such a bias is considered to be a terrestrial biomarker when present systematically in class of chiral compounds. An analytical protocol involving capillary electrophoresis (CE), liquid chromatography (LC), laser induced fluorescence (LIF), and time-of-flight mass spectrometry (ToF-MS) has been developed that shows great promise to detect such signatures in extremely low concentrations of organics. Further specificity toward extant life detection using such samples can be obtained by additionally applying modern biochemical antigen-binding methods such as with microarrays. To capture even a limited subset of this combined analytical power on a miniature platform, however, extensive and cross-cutting scientific and engineering evaluation is needed beyond what has been developed to date under individual sensor efforts.

Another effective route to combining expertise and methods may not attempt to define instrument suites *per se*, but rather to look at how well-established or developing miniature instruments can work, as a group, to address science normally done using multiple lab-scale facilities (and over long periods of time). Such an activity could be accomplished by organizing analog sample analysis "round-robins" with various participants receiving aliquots of complex samples as blinds, along with limited reconnaissance-type data about their collection environment, and tasked with making conclusions about their origin and evolution. This process may also help NASA determine the efficacy of investing in methods that have lab-scale heritage but have not yet appeared on the "*in situ* stage." For example, is it worth looking into, and could there be a flight-worthy version of techniques such as metagenomics, ion probe mass spectrometry and ion beam sectioning, nuclear magnetic resonance, or any number of very powerful sample preparation protocols found in an analytical chemical laboratory? Or is sample return required for all but the simplest samples and analyses? Furthermore, can these techniques the sufficiently automated that a non-specialist astronaut can perform the experiments on a martian or lunar base? Only a collection of the right scientists with the right background can begin to answer these questions. NAI has this collection.

Team Players: This is relevant to all teams, particularly obvious players would be researchers who emphasize Mars, geochemistry, microbiology, biomarkers, and instrument development. Members of GCA and CIW have already expressed interest. However, there are clearly members of other centers who could make important contributions (e.g. IPTAI, Ames, MBL, PSARC, LASP, UHNAI, UCLA, UCB)

Team Players: Goddard, UCLA, PSARC, Carnegie, Arizona, plus others (? TBD).

28. Astrobioenergetics: A "follow the energy" focus for astrobiology (Hoehler, DesMarais, ARC)

A key challenge in astrobiology is to build an understanding of life and its interaction with the environment based on a single (albeit highly diversified) example, and yet do so with a level of generality sufficient to embrace alternative models of biochemistry. In particular, the growing inclusion of astrobiology goals in mission planning and architecture emphasizes a practical need for broad-based concepts of habitability and biosignatures. Without such concepts, target selection, payload definition, and data analysis may risk overlooking a significant part of the spectrum of possibility.

All organisms, known or unknown, share in common a dependence on energy. This dependence defines the link between organism and environment at its most fundamental level. From it flow concepts of habitability and biosignatures that have potential to be all-embracing with respect to diverse forms of life, and yet amenable to quantification by reference to thermodynamics. We propose a focus on the energetic relationship between life and environment as an organizing theme for research within the NASA Astrobiology Institute.

30. Habitable Zones on Extrasolar Super Earths (Schrenk, Seager, CIW)

With the acceleration of discoveries of smaller extrasolar planets to be expected from refinements in computer software and spectrometer hardware, the question naturally arises as to whether there may be habitable zones associated with rocky planets several to a few tens of times more massive than Earth. Surface gravitational attraction scales approximately as radius for such bodies, so depending on atmospheric mass the near-surface pressure and temperature environments might be quite different from those on the ancient and modern Earth. The extent to which life as we know it might find a habitable zone on a "super Earth" now warrants attention. Studies continue of the effects of extremely high pressures, with and without the burden of higher temperature, on microbial growth and activity. Experiments to date indicate that life is not immediately extinguished when subjected to pressures 20,000 times ambient. In parallel, astronomers seek spectral features that may be biomarkers on extrasolar planets. The search for metabolic strategies and environmental niches on and within super Earths and other planets, subject to the constraints of organic chemistry and physics, provides a stimulating area for collaboration among astronomers and biologists. More generally, the consideration of planets and life different from those in our Solar System with the goal of formulating new ideas regarding what constitutes a habitable environment (beyond merely the conditions under which water is liquid) should continue to be a critical topic for astrobiology and serve to inform future NASA Discovery-class missions.

31. Exogenous Delivery Of Organic Volatiles And Water To Earth-Like Planets (Mumma, GSFC)

The origin and evolution of organic volatiles and water are central to understanding the formative aspects of young planets, especially of environments suitable for the emergence and sustenance of life. Studies of primitive bodies in our planetary system and of volatiles in circumstellar disks around young stars are required. Condensed phase organics can be identified at moderate spectral resolution ($R<1000$), but both high spectral resolving power ($R > 40{,}000$) and broad spectral grasp are needed to sample multiple gases (and their rotational temperatures) simultaneously (water, organics, nitriles, and deuterated isomers). Such measurements are a necessary precursor to a spaceborne observatory that can fully exploit high resolution spectroscopy of such targets.

Up to a dozen chemically-linked organic volatiles and water are now regularly measured in predictable comets, and several distinct cometary classes have been identified based on their icy composition. Obtaining a significant sampling of comets at infrared wavelengths has been hampered because CSHELL is outdated, and only very limited time is available to the broad community on Keck, and just a fraction of that for solar systems studies. The extension to less abundant species (isotopes, isomers, etc.) requires that observing time be granted for bright comets, but these usually are newly-discovered Targets of Opportunity. The competitive Time Allocation process usually requires proposals four or five months before the semester begins (thus, ten to eleven months before it ends). Even if known in advance, the large over-subscription (5-fold on Keck-2 in 2007A) usually prevents winning more than a few half-nights.

A few of these chemical species (CO, CH_4, OH* …) have been measured in disks near Young Stars in the 3 - 5 μm region, and this companion field is now a hot area that promises to provide new insights into processing in proto-planetary disks. A key project would consist of echelle spectroscopy in the 3-5 μm wavelength region of a large number of star-disk systems. This spectral region contains transitions of numerous molecules of great interest for characterizing the structure and chemistry of disks, including H_2O, OH, CH_4, C_2H_2, C_2H_6, HCN, and CH_3OH. The excitation temperature and column density of individual molecules can be mapped as a function of radius by modeling the velocity-resolved line profiles, giving data on chemical abundances, ionization fractions, and turbulence. When these data are coupled with realistic models of the thermal, chemical and excitation structure of disk atmospheres, one can unravel the vertical disk structure and ascertain the dominant chemical and heating processes.

We propose to consider two approaches to ensure adequate observing time for these two areas:

1. Provide guaranteed access to NIRSPEC at Keck-2. Purchase 2 nights at three - month intervals (8 full nights per year), with override priority for favorable comets (organics, D/H in water, etc). If no favorable comets are available, the time would revert to disk chemistry studies; the allocation would work out to 50-50 on average, I think.

2. Develop NAI advocacy to help ensure NASA (SMD) funding for iSHELL (CSHELL-2) at IRTF. Comets are brightest when close to the sun, and this often means that daytime observations are needed. IRTF is the sole telescope that permits daytime operations, but the present high-dispersion infrared spectrometer is obsolete. iSHELL will correct this deficiency, and indeed will surpass the capability of NIRSPEC at Keck-2. iSHELL will feature an immersion grating, will have R=60,000, be cross-dispersed (2Kx2K array), and be optimized for L and M - bands, the KEY region for polyatomic volatile species. M. J. Mumma will provide the 512Kx512K IR slit viewer (as he did for SpEX).

Team Players: Goddard, Hawaii, UCLA, plus others (? TBD).

32. Spectroscopic Characterization Of Exoplanet Atmospheres (Mumma, GSFC)

The recent detection of thermal emission from several transiting exoplanets using Spitzer (Deming et al. 2005, 2006, Charbonneau et al. 2005) proves that the infrared flux from these exoplanets is significant (up to 0.005 of the stellar flux). Spitzer has also detected a substantial day-night temperature contrast on the planet Ups And b (Harrington et al. 2006), demonstrating that large phase variations in IR intensity can occur. Doppler deconvolution is a technique that can extend the Spitzer exoplanet detections to ground-based telescopes. This technique uses the large orbital radial velocity of close-in exoplanets, in order to separate the spectrum of the planet and the parent star. The orbital radial velocity of a planet orbiting a solar-type star with a 4 day period (common for exoplanets) approaches 150 sin(i) km/sec. This causes a large periodic wavelength displacement of the planetary lines. The phase of this displacement (but not the amplitude) is precisely known from the reflex radial velocity of the star itself (used to discover the presence of the planet). The unique character of this varying planetary spectral signal is what allows Doppler deconvolution to separate the planetary spectrum from the telluric and stellar spectrum. Since the planetary molecular lines are numerous, narrow, and spread over large regions in wavelength, their detection by Doppler deconvolution requires a high resolution IR spectrograph with large wavelength coverage, but it does not require the photometric stability of a space-borne telescope like Spitzer.

As an example of Doppler deconvolution, a sensitive search for methane at 3.3 microns in the spectrum of the planet orbiting Tau Bootis was made using Doppler deconvolution of IRTF/CSHELL data by Wiedemann et al. (2001). For this technique, wavelength coverage is equivalent to telescope aperture, and iSHELL will improve sensitivity by a factor of 6.6, assuming optical efficiency similar to CSHELL. This is equivalent to upgrading the telescope aperture to 20 meters, and will not only detect the Tau Bootis planet's spectrum at 13-sigma significance, but also yield information on its orbital phase dependence. Extention to other favorable volatile species and lower mass, potentially life-bearing, planets will be feasible.

Team Players: Goddard, Hawaii, UCLA, Arizona, plus others (TBD).

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34. Space-based astronomical observations of developing habitable planetary systems (Des Marais, ARC)

Current observations of young stars and evolving disks are providing key insights about the formation of habitable planetary systems. Theoretical groundwork is required now to help guide observations by the upcoming Kepler, SOFIA, James Webb missions. This topic addresses the early physical and chemical evolution of habitable planets and the simulation of terrestrial planet growth in binary star systems. The Spitzer mission data will reveal processes that affect the formation of habitable planetary systems. Key factors that should be addressed include dispersal of disks by photoevaporation and viscous evolution, and the likelihood of planet formation as a function of the mass of the central star, since massive stars photoevaporate their disks on extremely short timescales. The goal of the upcoming Kepler mission is to identify earth like planets in other solar systems, including the formation of such planets in binary systems. Another key topic is the chemical evolution in protoplanetary disks and the location of the "snow line" separating water vapor and water ice. The condensation front associated with water and other species may have important ramifications regarding the location and composition of habitable planets. Predicting the isotopic composition of the protoplanetary disk with respect to its most abundant species might become another key approach to understanding processes for formation of habitable planetary systems.

35. Late Heavy Bombardments and Habitability (Weinberger, CIW)

The goal of this task is to connect measurements of meteoritic mineralogy and organic content to observations of circumstellar disks to study the volatiles that can be delivered to terrestrial planets during times of extreme bombardment. Laboratory measurements will be performed as needed to obtain quantities useful for modeling of astronomical data, such as indices of refraction. Model grains will be based on measured compositions to optimize observations to be made with the James Webb Space Telescope and Discovery-class missions that could image extrasolar planetary systems.

36. Origin of Earth's Water [Meech, UHNAI]

The origin of Earth's water is one of the important outstanding issues in the understanding of solar system formation. The location of the regions within the nascent solar system which may have fed water-rich material to the Earth during accretion is under debate. Chemical fingerprints of source regions for the water come from isotopic ratios (D/H) found in Earth’s oceans, which are high compared to the solar nebula material out of which Earth formed. Comets and asteroids (meteorites) have been proposed as source material, but there are chemical and dynamical problems associated with these as sources. Understanding the origin of water on terrestrial planets has implication for investigating the habitability of extrasolar planets in habitable zones, and is closely coupled with aspects of the space exploration vision both scientifically and in understanding likely location of space resources. Interdisciplinary exploration of the sources for Earth’s water provide opportunities not only for answers to fundamental astrobiology questions, but possibilities for instrument development (the next generation of infrared instrumentation for NASA ground-based facilities that support missions), but potential for development for new small and medium class mission development.

There has been considerable interest in water on the Moon, in particular as a resource, but I don't believe that this community has talked with the various communities that are approaching the issue from the dynamical delivery perspective or those looking at the origins from chemical perspectives. A focussed workshop could bring together members of these communities to disscuss these issues to identify areas where there is need for research focus to better understand the problems, and to identify specific measurement objectives from space missions that will address these questions, as well as specific new instrumentation development or targeted observation strategies. As an example of the type of questions that might be addressed, dynamical models which simulate the delivery of water to the inner solar system by asteroidal planetary embryos make some assumptions on the growth and existence of the gas giant planets in the system – how sensitive are the results to these assumptions? Given what we are learning about thermal properties of small body regoliths, what is the lifetime and depth of possible sub-surface ice on airless bodies? Interdisciplinary researchers within the NAI are key to asking the key questions and identifying where cross-cutting interdisciplinary approaches can address issues which are central scientifically and programmatically to successful execution of missions in the Vision.

<u>NAI Collaborators:</u>

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UCLA: Ed Young, J. Lyons
Goddard: Mike Mumma
Tennesse State: Todd Gary